

# The liquid-hydrogen absorber for MICE

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**Abstract.** This paper describes the liquid hydrogen system constructed for The Muon Ionization Cooling Experiment (MICE); MICE was built at the STFC Rutherford Appleton Laboratory to demonstrate the principle of muon beam phase-space reduction via ionization cooling. Muon beam cooling will be required at a future proton-derived neutrino factory or muon collider. Ionization cooling is achieved by passing the beam through an energy-absorbing material, such as liquid hydrogen, and then re-accelerating the beam using RF cavities. This paper describes the system creating the 22 l of liquid hydrogen within the MICE beamline; the necessary safety engineering, the liquid hydrogen absorber and its associated cryogenic and gas systems are presented, along with its performance.

## 1. Introduction

The Muon Ionization Cooling Experiment (MICE) [1] was built at the STFC Rutherford Appleton Laboratory to demonstrate the principle of muon beam phase-space reduction via ionization cooling. Muon beam cooling will be required at a future proton-derived neutrino factory or muon collider. Ionization cooling is achieved by passing the beam through an energy-absorbing material, such as liquid hydrogen, and then re-accelerating the axial component of the beam using RF cavities. For this purpose a complete system capable of safely condensing hydrogen gas in a vessel with thin aluminum windows was designed, constructed and operated [2]. This vessel was placed in the bore of the focus-coil magnet of MICE and was irradiated with a beam of muons. This enabled the MICE collaboration to measure the loss of energy and change of trajectory of muons in liquid hydrogen.

The muons for MICE were created from the decay of pions produced when a target dipped into the circulating proton beam in the ISIS synchrotron at the STFC Rutherford Appleton Laboratory (RAL). The beam was transported through momentum selecting dipoles and a decay solenoid to the cooling channel. The cooling channel consisted of a superconducting magnet lattice within which the hydrogen



absorber was placed. Upstream and downstream of the absorber were tracker modules which measured the trajectory of individual muons from which beam emittance was derived.

This paper describes the containment vessel for the liquid hydrogen and its associated systems including the safety engineering applied and the system performance.

## 2. Safety considerations

The MICE hydrogen system was designed to store 22 l of liquid hydrogen in an aluminium vessel at  $\sim 20$  K, slightly above atmospheric pressure. Hydrogen/air mixtures are flammable over a wide range (4 % to 75 % hydrogen by volume) so preventing the ingress of air into the hydrogen system and the escape of hydrogen into the experimental hall was essential. The following principles were applied to the system design:

- The primary hydrogen containment system was enclosed within a secondary containment system - this was either a continuously-pumped vacuum or a volume continuously flushed with dry nitrogen gas; all exhaust gas which had potential to contain hydrogen was vented to atmosphere at a concentration well below the Lower Explosive Limit (LEL) of 4 %.
- The entire hydrogen system, i.e. primary and secondary containment, was engineered to be robust to two unrelated failures, whilst maintaining safety in operation.
- During operation, air leaking into the vacuum would plate on cold surfaces; this had potential to cause an explosive risk in the case of a hydrogen leak into the vacuum. The maximum permissible leak rate into the vacuum was calculated to limit the volume accumulated over the operating period of the experiment to a safe value.

## 3. Overview of gas flows

A schematic of the flows in the hydrogen gas system is shown in figure 1 with all the key elements. This system was fabricated entirely from stainless-steel components. Pipework was welded wherever possible, X-rayed to ensure DSEAR [3] compliance where required, and non-welded joints were sealed using metal gaskets.

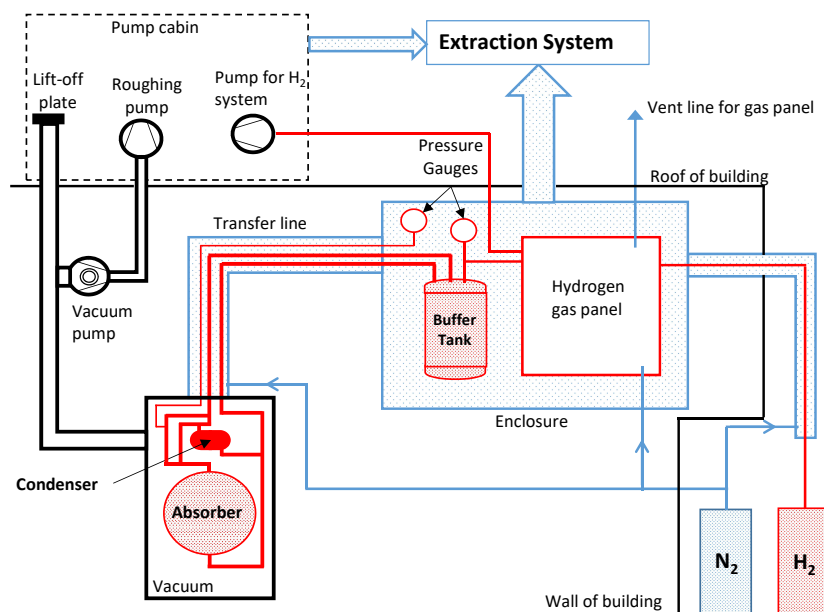
Hydrogen gas was piped from bottle racks at ground level outside the MICE hall, into a gas panel on the periphery of the experiment. From there the pipework took it into the hydrogen turret, where it was cooled by a Cryomech PT415 pulse tube in the condenser. The cold gas or liquid then sank through the pipework into the absorber itself. The condenser and associated pipework in the hydrogen turret were enclosed in a thermal shield which was cooled to 45 K by the first stage of the cryocooler; the second stage of the cryocooler was directly connected to the condenser. Multi-layer insulation (MLI) was used throughout the system to limit thermal loads. Space and beamline physics constraints prevented the use of a cooled thermal shield around absorber and its pipework; this would have improved the rates of cooling and liquefaction. The layout of the hydrogen system and absorber vessel within the magnet bore is shown in figure 2. Excess gas was returned via the gas panel and vented to atmosphere 4.5 m above the experimental hall.

As shown in figure 1, dry nitrogen gas was used to flush the secondary containment system around the warm pipework and through the gas panel; ultimately being expelled to atmosphere 4.5 m above roof level through the extraction system. Within this containment system were ten hydrogen sensors in nominal-redundant pairs at five positions, to warn of the presence of hydrogen leaks.

The cold pipework and absorber itself were contained within a vacuum space which was continuously pumped. The pumped gas was expelled into a locked and ventilated pump cabin on the roof of the experimental hall for safety reasons.

### 3.1. Control and monitoring system

The liquid-hydrogen control and monitoring (C&M) system was sited in a locked room adjacent to the experimental hall. It was designed to be stand-alone, based on programmable logic controllers



**Figure 1.** Gas flows in the hydrogen gas system. The helium gas used for initial flushing of the hydrogen volume, and during cooling, is not shown.

(PLC), and capable of operating without an external network connection to eliminate the possibility of unauthorised intervention. A touch-screen provided monitoring, allowed an operator to run pre-determined sequences such as 'Purge', 'Fill', and 'Empty', or control individual components (valves, pumps, compressor etc.). Keyed switches were provided to allow manual override (by authorised persons only) of certain automatic functions should this be required.

An uninterruptable power supply (UPS: Rello MST 20-T4-1) powered the control PLC, gas-detection system and the extraction system in the event of a power failure for a sufficient time to empty the system of hydrogen.

The intrinsically-safe explosion-protection method was used for all equipment in the gas panel and the sensors in the absorber, whereby the energy in control circuits is limited so that ignition of a hazardous hydrogen/air mixture cannot occur. Since the heaters attached to the absorber vessel and the coldhead could not be intrinsically safe, they were interlocked to prevent their operation unless the vacuum in which they were positioned was better than  $10^{-3}$  mbar. Layers Of Protection Analysis (LOPA) was applied to the whole control system.

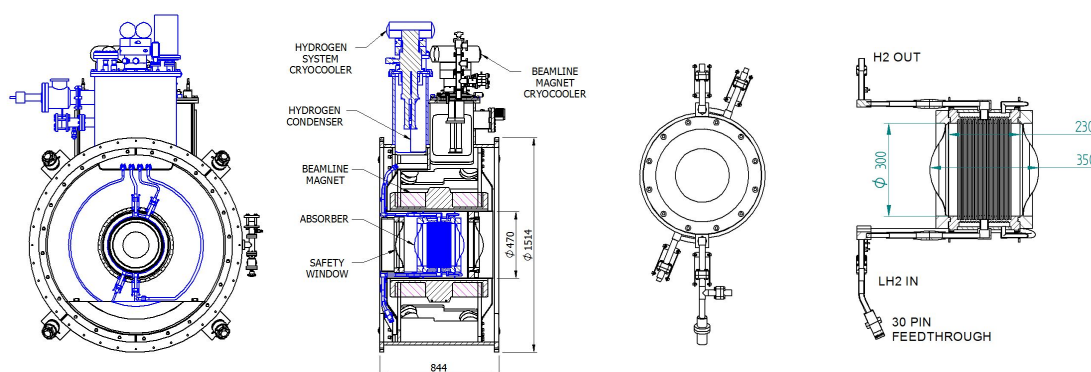
#### 4. Absorber vessel

The absorber vessel comprised a cylindrical aluminium body sealed with two thin aluminium end windows, attached with an indium-sealed flange; it contained the 22 l of liquid hydrogen through which the muons would pass. The absorber vessel sat in the centre of a focus-coil. Drawings of the absorber/focus-coil (AFC) module and the installed absorber vessel are shown in figures 2 and 3. Safety considerations, as described in section 2, required a secondary containment system. Therefore, the absorber vessel was situated in an evacuated space within two more thin aluminium safety windows, so the muon beam had to traverse four windows.

As a muon beam passes through material, some of the muons' kinetic energy is lost through ionization of the material. This process results in a reduction of the normalised transverse emittance and the beam is said to be cooled. Muons will also undergo multiple Coulomb scattering which increases the divergence

of the beam, thereby increasing the normalised transverse emittance and heating the beam. To maximise the cooling effect from energy loss in liquid hydrogen, while minimising the heating effect from multiple Coulomb scattering in the aluminium windows, these windows were required to be as thin as possible. The two aluminium windows on the absorber were designed to be  $180\text{ }\mu\text{m}$  thick at the center and the two safety windows each had a central thickness of  $210\text{ }\mu\text{m}$ .

The aluminium alloy chosen was 6061-T651. The yield strength was measured at room temperature to be  $39,900\pm 700\text{ psi}$  ( $275\pm 5\text{ MPa}$ ). The double-bend geometry, shown in the figure 3, increases the burst strength; the windows withstand internal vacuum with the vessel in atmosphere and test windows burst above 7.6 bar.



**Figure 2.** Drawing of the absorber integrated with the beamline magnet.

**Figure 3.** Detail of the liquid-hydrogen absorber vessel.

The thicknesses of sample windows were measured in two separate ways:

- One absorber and two safety windows were measured with the View Precis 3000 Optical Coordinates Measurement Machine (CMM).
- Low energy electrons are strongly attenuated by modest thicknesses of aluminium. Two different beta sources,  $^{90}\text{Sr}$  and  $^{204}\text{Tl}$ , were used to measure the thickness of a MICE window. The central thickness of an absorber window was measured to be  $178 \pm 6\text{ (stat)} \pm 4\text{ (fit)}\text{ }\mu\text{m}$ .

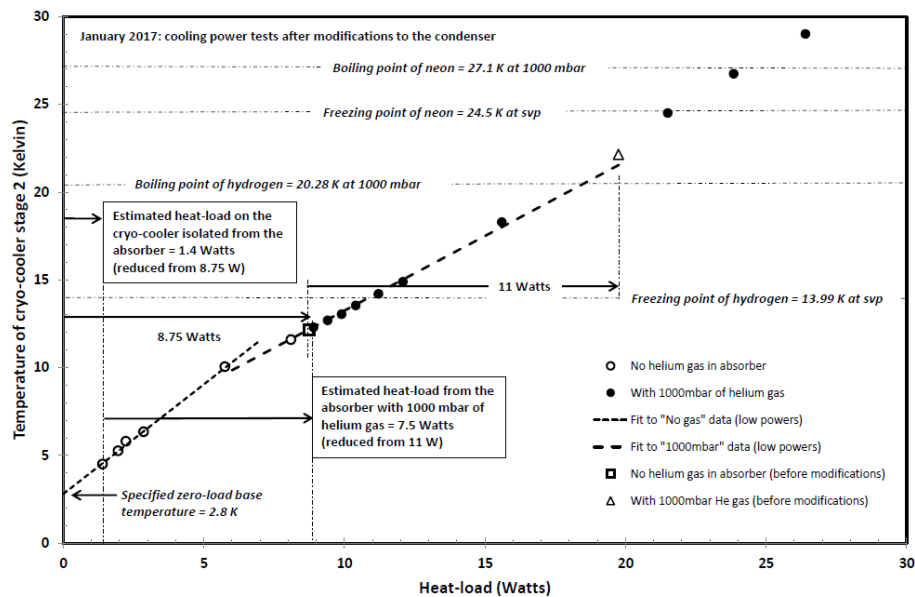
## 5. Performance

A system-verification test programme was carried out using helium and neon. The performance as measured with the system under vacuum and with 1 bar of helium gas is given in figure 4. The cryogenic performance of the system within the AFC was demonstrated by two tests; cooling the absorber to 19.5 K and later liquifying neon in the system. This gave the confidence required to progress to liquefying hydrogen.

In preparation for hydrogen filling, the absorber vessel was pre-cooled over four days using helium gas to transport heat between the condenser and the absorber vessel, at the end of which the coldhead second stage was 14.0 K and the absorber was 20.4-21.2 K.

After emptying the system of helium gas, hydrogen gas at 1150 mbar was introduced. The incoming gas warmed the condenser, and the automatically-controlled heater maintained the coldhead second stage temperature above 18 K to prevent hydrogen ice forming. Final cool-down and liquefaction of hydrogen took eight days. The liquefaction rate was almost uniform at just over 2000 bar litres per day. A total of  $\sim 16,300\text{ bar l}$  of hydrogen gas were liquefied.

The 22 l volume of liquid hydrogen was maintained for three weeks during MICE data-taking. The coldhead was then switched off and heaters, attached to the coldhead and absorber vessel, were switched on; the hydrogen gas vented to the atmosphere. Emptying the absorber vessel took approximately 5.5 hours, after which hydrogen was purged from the system.



**Figure 4.** The circuit's cryogenic performance. The coldhead's second-stage temperature is plotted as a function of heat-load (environmental thermal load plus Joule heating from a local heater). The data with the system evacuated was translated horizontally until the intercept on the temperature axis corresponded to the specified zero-load temperature of 2.8 K quoted by the coldhead's manufacturer. This estimates the environmental thermal load on the coldhead and condenser. Helium gas at  $\sim 1000$  mbar was introduced to the condenser which cooled the absorber vessel. The gas-load data were then aligned with the vacuum data to estimate the environmental thermal load on the absorber vessel.

## 6. Conclusions

A system to safely condense hydrogen gas in a vessel with thin aluminium windows was designed, constructed and operated. This vessel was irradiated with a beam of muons in the MICE experiment at RAL. Approximately 22 l of liquid hydrogen were collected in this vessel and stored in a stable state three weeks. This enabled the MICE collaboration to measure the energy loss and trajectory change of muons in liquid hydrogen, thus elucidating details of interactions leading to beam-cooling effects in liquid hydrogen.

## Acknowledgements

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